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Robust Rolling Horizon Optimisation Model for Offshore Wind Farm Installation Logistics

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Abstract
Our approach can be considered as both proactive and reactive, since uncertainty is considered both in creating the initial schedule and the schedule can be updated in real-time.

Keywords: Robust scheduling, Rolling horizon, Offshore wind farms, Installation operations

1. Introduction

Offshore wind is an important renewable energy resource of European Energy (The Crown Estate Review, year?). The capacity of the offshore wind farms (OWF) in Europe have been increasing since 2009 (Kaiser and Snyder, 2012) and this increase will continue to achieve the national targets set by European Union for renewable energy generation by 2020 (The Crown Estate Review, year?). UK has one of the largest wind energy potential in Europe, and is expecting to facilitate a capacity up to 33 GW by 2020 (The Crown Estate Review, year?). With the development of UK Round 3 and Scottish Territorial OWF sites, the OWFs are moving further from shore and increasing in generation capacity. The installation and commissioning costs are expected to be around 26% of the Capital Expenditure costs for the initial OWFs of Round 3 (Renewables Advisory Board, 2010), and they are identified as potential areas for cost reductions (Offshore Wind Cost Reduction Task Force, 2012).

A typical Round 3 OWF has over a hundred offshore wind turbines (WT), a number of offshore substation platforms (OSPs), inter-array (IA) cables connecting each WT to either another WT or to one of the OSPs, and a number of export cables connecting the OSPs to the shore. The installation process of these OWFs is a highly complicated process with many interrelated operations carried out by specialized vessels. A thorough planning should be made for the installation operations both to reduce the costs involved in the whole installation process and to reduce the total duration of the installation to start energy generation as soon as possible.

This study is motivated by three industry partners that are involved in the installation process of OWFs. We develop two optimisation models to schedule the installation operations that support key logistical decisions; hiring time interval for the installation vessels, hiring times for ports, activating asset arrival to ports etc. The first model is a deterministic optimisation model, which results in an overall schedule for the installation operations minimizing either the total cost or the total duration of the installation process. The second model is a robust optimisation model that finds the worst case duration of the installation process for a given percentage of deviating tasks. Both of these models can be used to find an overall schedule for the whole installation process, and to find new schedules when deviations from the baseline schedule occurs as installation progresses.

The structure of the paper is as follows: we describe the problem in Section 2 and present the literature in Section 3. The two models are explained in Section 4. We present the test results in Section 5 and conclude in Section 6.

2. Problem Definition

In this study, we consider the installation process of all assets of an OWF; OSPs, wind turbine generators (WTG), foundations, IA cables and export cables. The OWF installation is therefore made of five streams of installation operations, and the installation order of streams is as follows: OSPs, export cables, foundations, inter-array cables and WTGs. We further divide these five main assets to individual assets that result in nine key substreams: piles, jackets and topsides for OSPs, nearshore and offshore export cables, WT piles and jackets, inter-array cables and WTGs.

2.1 Installation Operations

The problem setting is given in Barlow et al. (2014) and we briefly summarize the operations for the sake of completeness. The installation process starts with the arrival of assets to their load-out ports, which is the last port the asset arrives before being transferred to site. The assets are then carried from the port to the OWF site by either their installation vessels or their support barges. If a stream is supported by barges, the assets are carried to the site by the barge, and the barge stays at site and feeds the installation vessel during the installation until its entire load is finished. Otherwise, the installation vessel carries the load to the site. The installation of each stream follows a number of operations in sequence. This sequence depends both on a number of operational decisions from the planner and on the characteristics of the installation vessels. The installation operations can be classified to two; asset installation operations and support installation operations. Asset installation operations are carried out by installation vessels and support installation operations are done by support vessels like crew transfer vessels. For each stream, there can be pre-installation support operations or post-installation support operations. Each installation operation starts after their predecessor operations finish, and the predecessor operations can be an operation from the same stream or an operation from another stream. For instance, for the WTG to be installed, all IA cables connecting that WTG and the foundation of that WT should be installed. The installation finishes after all the assets are installed and their post-installation operations are completed. The high level precedence relation of an OWF is given in Figure 1.

Each operation’s duration depends on the vessel performing that operation and the weather conditions. The wind speed and wave height are the limiting factors for most of the operations, and they should be under a limit for the operations to be completed. Some operations can be divided and carried out in shorter time intervals. For each operation, the weather conditions should be feasible for the operation to start, and the feasible weather window should be equal to at least the length of the operation’s duration (or the shorter time interval) to complete that operation.

The number of installation vessels for each stream is at most two, since it is impractical and unrealistic to use three or more vessels for each stream. However, the number of barges is not limited. The planner decides on the vessels and barges to be used for each stream. The planner may assign the same vessel to multiple streams. For this case, the vessel finishes each stream's tasks in order due to remobilisation (getting prepared for the next stream installation) requirement between each stream.

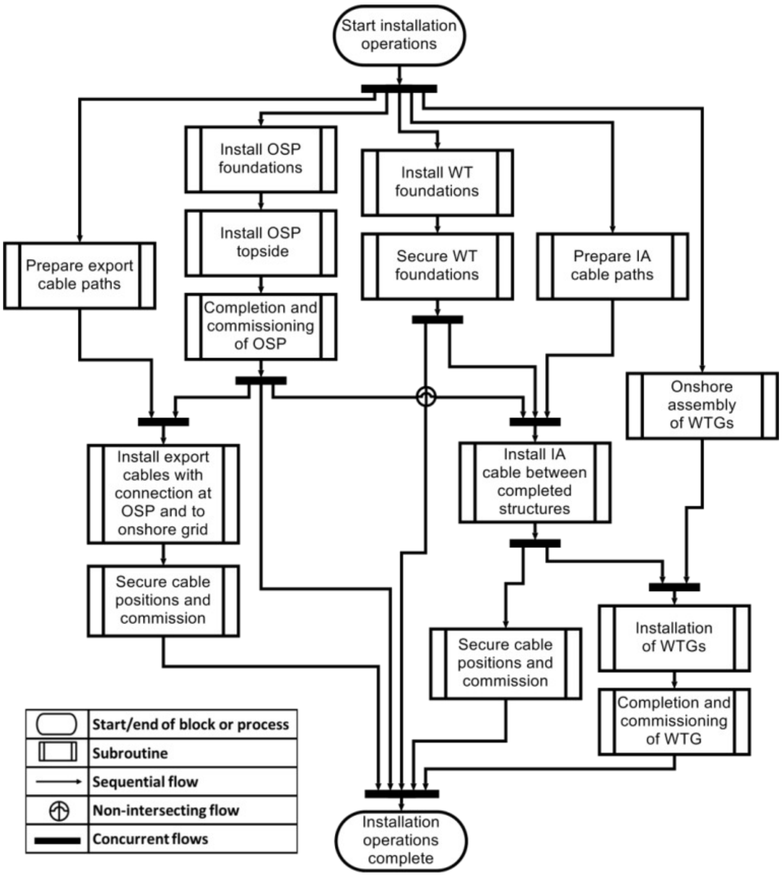

Figure 1: High level precedence relation between five main assets of an OWF (Barlow et al. 2015)

We assume that the location and layout of the OWF assets are determined before the installation starts. Also, for each stream, the order in which the assets are to be installed is also known. The assets are assumed to arrive at the load-out port in batches with a constant arrival rate.

2.2 Objectives

We consider the two objectives: minimising the total duration of the project and minimising the total cost of the project. The project cost is made of the following components: vessel chartering costs, port costs for single asset ports and multiple asset ports, support spread vessel costs and the costs of all support installation operations. A dayrate is agreed for the use of each vessel and the vessel chartering cost is calculated multiplying the vessel hiring duration; from the start of its mobilisation until its demobilisation; with its dayrate. Port costs are calculated for the duration that port is used, they can either be used by a single asset of by multiple assets. The support spread vessels can be used in a single stream or they can be used in multiple streams. Like the port costs, they are calculated for the duration they are used. Support installation operation costs are calculated for their durations. The installation technician and vessel crew costs are included in the vessel dayrates and support installation operation costs. The vessel chartering costs dominate the installation costs since the installation vessels are few in number and they are highly specialized for the tasks involved (Renewables Advisory Board, 2010). Delaying the vessels may result in high costs and in vessel unavailability since the vessels may be contracted to other firms. The time intervals to hire these vessels, the support spread vessels and the ports should be planned well in advance.

2.3 Limitations

Each industry partner agrees upon first, mid and full generation dates with the government. The first generation date is the date that at least one WTG can start generation. For this, the WTG and all assets connecting it to the onshore grid (the OSP that it is connected to, the IA cables linking the WTG to the OSP and the export cables of the OSP) should be installed. By the mid generation dates, the contracted percentage of WTGs, and their corresponding IA cables, OSPs and export cables should be installed. All assets of the OWF site should be installed by the full generation date.

Some vessels can have activation dates as they may not be ready at the start of installation due to their availability. Similarly, some support installation task sets can have activation dates since the weather conditions of certain periods in a year may not be favourable for those operations to start. Therefore, a ready time is included for the first task assigned to the vessels with activation dates and to the tasks in the support installation task sets.

All vessels, ports, support installation task sets and support spread vessel costs can have non-operational periods that they are not used. For instance, some vessels may be sent back to their suppliers in the winter months, during which they are not as efficient as the summer periods. These non-operational periods are not included in the cost calculations, since they are planned in advance and the related ports or vessels are not used for those durations.

3. Solution Approach

For a given installation scenario, the optimisation models provide estimates for the project cost and duration. The planner inputs the characteristics of the OWF such as the number of WTGs, OSPs, IA cables and export cables, the vessels and the barges to be used in each stream, vessel dayrates, port costs, operational decisions, export dates, non-operational periods for all vessels and ports, and activation dates. For each given scenario, the models find the start times of all tasks, the operating periods of vessels and streams, the total project cost and total project duration for the resulting schedule.

The first model is a deterministic model that optimizes either the total duration or the total cost of the project. Every parameter, such as task durations, activation dates, non-operational periods, is considered as deterministic. The second model is a robust optimisation model that includes the most prevailing uncertainty in the project; the uncertainty in task durations.

Assuming that the task durations vary within a range, the second model finds the worst possible project duration for a percentage of deviating tasks.

For both of the models, we have an initialization stage in which we assign the tasks to the vessels for a given scenario. For an installation project, the planner selects the installation vessels for each stream and assigns the installation order of the assets. Given the vessel capabilities for each asset stream, we construct the routes with the asset-vessel-assignment algorithm explained below. The algorithm assigns assets to the vessels that carry them to the installation site. Knowing the asset groups carried by the vessel at each departure from the port, the routes are constructed. As inputs, we have the vessel capacities, the duration of the tasks for each vessel, the installation order of the assets, and the barge information, if any barge supports the installation. There are two ways of bringing the initial load to the site; the installation vessel can directly go to the site and wait for the barge to start installation or it can carry an initial load and start installation directly. Thus, for the case when barges are used, the capacity of the barges, and the decision of carrying the initial load by the installation vessels are required additionally. We give the general structure of the algorithm first and explain it in details.

Let the set of installation vessels be V, the set of barges be B, capacity of installation vessel $v \in V$ be cap_v_v, capacity of barge $b \in B$ be cap_b_b, $a_i \in A$ be the asset to be installed at i^{th} order, and $Assets\_v_v$ be the set of assets assigned to vessel v, and $Assets\_b_b$ be the set of assets assigned to barge b. Let s_v_v be the time that vessel v is ready for the next installation. Before executing the algorithm, the ready time of each vessel is set to the summation of its activation date and mobilisation duration. During the algorithm, this value is updated as assets are assigned to the vessels. Let t_v_v be the expected time the vessel finishes the next asset's installation. Let the installation vessel v's expected duration of loading be $load\_v_v$, transit to site as $transit\_v_v$, operations before installation be $pre\_install_v$, installation duration be $install\_v_v$, and operations after installation denoted as $post\_install_v$. Similarly, we have $load\_b_b$ and $transit\_b_b$ duration for barge b. The installation time from barge might be different for different installation vessels, therefore we denote the installation duration from installation vessel v by barge b as $install_{vb}$. A barge shadows an installation vessel entirely until the barge's load finishes, so that the installation vessel and barge are assigned to each other for that duration. We denote the index of installation vessel assigned to barge b as $match_b$. For installation with barges, we have additionally have the ready times that both barge and installation vessel are ready to start installation at site. We denote the ready times of installation vessels as $ready\_v_v$, and barges as $ready\_b_b$.

Asset-Vessel-Assignment Algorithm

For $i = 1$ to $|A|$ do

Find installation finish time of installation vessels

For $v = 1$ to $|V|$ do
If $B = \emptyset$ or $cap\_v_v > 0$ then
If $|Assets\_v_v| = 0$
$t\_v_v \leftarrow s\_v_v + load\_v_v + transit\_v_v + pre\_install_v + install_v$

```
                Else
                        If B = ∅
                            If |Assets_v_v| = k.cap_v_v for k ∈ ℤ+
                               t_v_v ← s_v_v + post_install_v + transit_v_v + load_v_v +
                                         transit_v_v + pre_install_v + install_v
                            Else
                               t_v_v ← s_v_v + post_install_v + pre_install_v + install_v
                            End if
                        Else
                            If |Assets_v_v| < cap_v_v
                              t_v_v ← s_v_v + post_install_v + pre_install_v + install_v
                            Else
                              t_v_v ← ∞
                            End if
                        End if
                End if
        Elseif
        t_v_v ← ∞
        End if
        End for
```

Find installation finish time of barges shadowing installation vessels

```
        For b = 1 to |B| do
                If |Assets_b_b| = 0
                ready_b_b ← s_b_b + load_b_b + transit_b_b
                Else
                        If |Assets_b_b| = k.cap_b_b for k ∈ ℤ+
                        ready_b_b ← s_b_b + transit_b_b + load_b_b + transit_b_b
                        match_m ← ∅
                        Else
                        ready_b_b ← s_b_b
                        End if
                End if

                If match_b > 0
                  v ← match_b
                        If |Assets_v_v| = 0
                        ready_v_v ← s_v_v + transit_v_v + pre_install_v
                        Else
                        ready_v_v ← s_v_v + post_install_v + pre_install_v
                        Endif
                        For v = 1 to |V|, v ≠ match_b
                        ready_v_v ← ∞
                Else
                For v = 1 to |V| do
                    If match_b ≠ v for b = 1 to |B| do
                            If |Assets_v_v| = 0
                              ready_v_v ← s_v_v + transit_v_v + pre_install_v
                            Else
```

$ready\_v_v \leftarrow s\_v_v + post\_install_v + pre\_install_v$
Endif
Else
$ready\_v_v \leftarrow \infty$
Endif
End for
$d\_match_b \leftarrow argmin_{v \in V}\{ready\_v_v\}$
Endif
$t\_b_b \leftarrow \max(ready\_v_{d\_match_b}, ready\_b_b) + install_{d\_match_b b}$
End for

Assign the next asset to a vessel

If $min_{v \in V}(t\_v_v) < min_{b \in B}(t\_b_b)$
$n \leftarrow argmin_{v \in V}\{t\_v_v\}$
$s\_v_v \leftarrow t\_v_n$
$Assets\_v_n \leftarrow Assets\_v_n \cup \{a_i\}$
If $B \neq \emptyset$
$cap\_v_n \leftarrow cap\_v_n - 1$
Endif
Else
$m \leftarrow argmin_{b \in B}\{t\_b_b\}$
$s\_b_m \leftarrow t\_b_m$
$Assets\_b_m \leftarrow Assets\_b_m \cup \{a_i\}$
$match_m \leftarrow d\_match_m$
$s\_v_{match_m} \leftarrow t\_b_m$
$Assets\_v_{match_m} \leftarrow Assets\_v_{match_m} \cup \{a_i\}$
Endif
Endfor

The assignment of assets to vessels is done in accordance with their installation order. The underlying principle in the algorithm is to assign the next asset to be installed to the vessel that could finalize the next installation sooner. For this, we find the expected installation finish times of all the vessels given their current placements and their loads so far. In the first loop, we find the installation finish times of the installation vessels if the asset stream is not supported by barges or if there are barges but the installation vessel carries the initial load to the site. If there are no assets assigned to that installation vessel yet, we sum the durations of loading, transiting, pre-installation operations and installation to find the expected installation finish time of the first asset assigned to that vessel. If there are already assets assigned to that vessel, we check if the vessel currently carries at least one asset. For this, we compare the total number of assets assigned to that vessel and the capacity of that vessel. If the total number of assets is equal to a multiple of the capacity of that vessel, then the previous asset that is installed by the vessel should be its final load. Thus, the vessel needs to go back to port to reload. Otherwise, the vessel can continue installation at site. If the vessel is supported by barges and its first load is finished, or if the vessel does not have any capacity and barges carry the entire load, the installation vessels are assigned a high value of installation finish time, since they require a barge to continue installation.

The next loops find the installation finish times if barges are used to support installation. Since barges only take part in transportation of assets to the site, they supply one of the installation vessels each time they go to site, until all their loads are finished. Since the barge and the installation vessel should move together during their assignment, we find their ready times, which is the time that the vessels are ready to continue with installation of the next asset. If the barge is assigned to one of the installation vessels, only that installation vessel's ready time is considered. Otherwise, from the installation vessels that are not supplied by any barge, the one with the smallest ready time is temporarily matched with that barge. The installation finish time is then the summation of the maximum of the ready times among the matched vessels and the installation duration of the asset from that barge.

The final if-else set makes the asset-vessel assignment. Among all the vessels, the next asset is assigned to the one that finishes the installation in the shortest duration. If the asset is directly assigned to an installation vessel, the capacity of that vessel is decreased when there are barges supporting that asset's installation. This reduction makes sure that the vessel is only assigned assets for its initial load and no additional assets are assigned to it beyond its capacity. If the asset is assigned to a barge, the asset is assigned to both the barge and the matched installation vessel. The installation vessel is matched to the barge if it is not already and their start times are updated with the installation finish time.

If more than one vessel results in the minimum duration, to break the ties, we assign the asset to the vessel with more tasks previously assigned. If also the task numbers are the same, we randomly select one vessel. This method always results in selecting the barge with the maximum workload. Therefore, if the planner assigns three barges to a stream but two barges are satisfactory to carry out all the tasks without any delay, the model only assigns tasks to those two barges. The resulting task assignment suggests the minimum number of barges that can be used in each stream. The real-time planning could require more barges, since there may be delays due to weather conditions. In this assignment model, we do not consider those delays and use the expected durations for all the tasks.

This algorithm results in assignments of assets to vessels that consider their installation order. Knowing which vessel carries and installs which asset, we derive the routes of each vessel, the tasks of each vessel, the durations of these tasks, and the precedence relations between the tasks. The initialization stage results in a project scheduling problem without resource constraints that can be solved with either the deterministic or the robust model.

We develop a mixed integer linear programming model for the project scheduling problem. In the initialization stage, we find task-vessel and task-substream assignments. Similarly, we know all the substreams that the cross-stream vessels and the marshalling ports are used for. For all vessels and streams with activation times, we include their initial tasks to set T_r (set of tasks with a ready time), and set their ready times to the corresponding activation dates. For the constraints on generation dates, we find the final tasks that should be finished by the generation dates. These tasks are included in set T_{dd} (set of tasks with due date) and their due dates are set to the export dates. Suppose we have N-1 tasks in total. We obtain a fully connected graph for these tasks, in which nodes correspond to the tasks and arcs correspond to precedence relations between tasks. For this, we first include two more tasks, task 0 being the initial task and task N being the final task. We then add tasks $i \in T$ without an immediate predecessor to set T_r (set of tasks with a ready time) and if they do not have ready times yet, set their ready times, r_i, to 0. We include $(0, i)$ to IP for tasks $i \in T_r$. Similarly, we add (i, N) to IP for tasks $i \in T$ without an immediate successor.

The planner can choose to optimise one of the objectives and put a bound on the other objective. We ensure obtaining solutions that are efficient by the ε-constraint method.

The planner chooses the objective to be optimised and the upper bound on the other objective. Starting with the extreme nondominated points, the planner observes the range of values each objective function can take. Varying the upper bound within that range, different nondominated points can be obtained.

The deterministic method develops a schedule without considering any uncertainty. However, many parameters may vary due to uncertainties; task durations may vary due to weather conditions or due to expertise of crew, some of the vessels may breakdown and require repair at port for significant durations, arrival of assets may fall behind schedule etc. With the guidance of the industry partners, we determine the most prevailing uncertainty as the task durations.

Project planning under uncertainty is addressed in many studies, see Herroelen and Leus (2005) for a review on the problem. Stochastic programming approaches, fuzzy project scheduling, robust approaches are some of the methods to schedule operations under uncertain task durations. All methods require different knowledge of the uncertainty. For stochastic programming, mostly the probability distributions of the random variables should be known. For fuzzy scheduling approaches, a membership function is required that maps different values of the uncertain event to values between 0 and 1. In robust optimisation approaches, the range that the uncertain variable can take values should be known. Considering that all tasks in our study have variability in their durations, the approach that requires the least knowledge on the uncertainty fits our case the best. Since the data requirement is considerably fewer for robust optimisation approaches, we choose to continue with this approach.

Robust optimization is first considered in Soyster (1973). He considered the uncertainty in the constraint matrix and tried to find a solution to the problem where the uncertain parameters are all assigned to their most restricting values. Later, Ben-Tal and Nemirovski (1998) considered a less conservative approach, in which the uncertain parameters have ellipsoidal uncertainty sets and suggested nonlinear models. In 2002, Bertsimas and Sim developed another approach that allows a subset of uncertain parameters to vary within their value range. The proposed robust model is linear, and they provide a probabilistic guarantee for the robust solution to be feasible for different values of the uncertain variables. Their approach is applicable to uncertainties both in constraint coefficients and in objective function coefficients (row-wise uncertainty). Gabrel et al. (2014) surveys the recent advances in robust optimization.

We employ an approach similar to Bertsimas and Sim's (2002) approach. Although the approach is similar, there are fundamental differences with their approach. Firstly, we consider uncertainty in task durations, which correspond to right-hand-side values of the constraints.

Thus, we have column-wise uncertainty as opposed to the row-wise uncertainty in their approach. Additionally, the uncertainty in task durations may affect more than one constraint, if the uncertain task is a predecessor of more than one task. In their approach, the uncertainty affects only a single row; either the objective function, or one of the constraints.

The literature on uncertainty in right-hand sides is scarce. Gabrel and Murat (2010) consider the uncertainty on right-hand sides when the right-hand sides take values from an interval. They use duality theory to show some properties of uncertainty in right-hand sides. Minoux (2011) propose a 2-stage algorithm for robust optimization with uncertainty in right-hand sides, and demonstrate the algorithm on robust PERT scheduling (Minoux, 2007). In their approach, the task durations vary between a nominal value and a maximum value. An upper bound, $\Gamma \in \mathbb{Z}_+$, is put on the number of task durations that can deviate from their nominal values. In our robust approach, we solve the makespan minimization problem. In our case, given all tasks are defined, we assume $d_i \in [d_{i,min}, d_{i,max}], i \in T$, where $d_{i,min}$ is the nominal value (under no deviation), $d_{i,max} = d_{i,min} + d_{i,inc}$, and $d_{i,inc}$ is the range of duration values for task $i \in T$. We next give the mathematical model.

(P1) Minimise t_N (52)

s.t. $$t_j - t_i \geq \begin{cases} d_i & (i,j) \in IP, i > 0 \\ r_j & (i,j) \in IP, i = 0 \end{cases} \quad (53)$$

$$-t_i \geq d_i - dd_i \qquad i \in T_{dd} \quad (54)$$

$$t_0 \geq 0 \quad (55)$$

Here, we do not include the non-operational periods to the model for simplification purposes. However, Minoux's (2007) approach cannot be directly applied to our model due to constraint (54). This constraint may not allow some tasks to be assigned to their maximum durations, and some tasks may be assigned a duration between their nominal and maximum values. Therefore, in our approach, Γ may turn out to get a value larger than the total number of deviating tasks. Despite this fact, we refer Γ as the maximum number of deviations.

As indicated above, we solve model (52)-(55) given all tasks, all task durations, and the precedence relation between the tasks are defined. For this, we use the asset-vessel assignment algorithm explained before.

The solution of the robust model provides all task durations and the critical path. The tasks that are not on the critical path can start at different time points without delaying the total project duration, therefore the results of the robust solution does not provide information on the non-critical tasks. To come up with a schedule that considers also the total cost of the project and meaningful start times for the non-critical tasks, we solve a separate model

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